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Analysis of Production Response to CO_2/Sand Fracturing: A Case Study

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ABSTRACT

The U.S. Department of Energy, Petroleum Consulting Services, Universal Well Services, and Canadian Fracmaster have recently performed eight CO_2/sand stimulations on four Devonian Shale gas wells in the Appalachian Basin. Four two-stage CO_2/sand stimulations were executed with two operators in the Pike and Martin County, Kentucky area. All stimulations involved 120 tons of carbon dioxide (CO_2) and up to 47,500 pounds of sand. In addition, there are eleven existing control wells stimulated with four two-stage foam fracs and seven two-stage nitrogen fracs. Production results from these fifteen wells are compared. After nine months of production, CO_2/sand fractured wells in the Pike County, Kentucky study area are nearly twice as productive as nitrogen gas fraced wells and nearly five times better than the foam fraced wells in the study group. The per well incremental gas production after nine months ranged from 13.5-22.2 MMcf per well for nitrogen gas and foam fraced wells, respectively. Discussion of the CO_2/sand treatment parameters, job execution, and a representative pressure/injection response are discussed in detail. As the operators begin to utilize the CO_2/sand frac process on more wells, the new stimulation process will become commercially available on a routine basis.

BACKGROUND/HISTORY

The first publicly documented use of the CO_2/sand stimulation process was in 1982[1]. Early field testing of the stimulation process proved highly successful for gas well applications[2]. Laboratory testing and numerical modeling continued to evaluate proppants and fluid rheology[3-6]. Advantages and limitations had been identified by Lancaster and Sinal[7,9] as early as 1986. By 1987, more than 450 jobs had been executed in Canada[8]. The CO_2/sand frac technology has widespread commercial acceptance by operators in Canada. The technology has yet to be fully demonstrated in the U.S. beyond some early testing in the mid 80's. Hence, the U.S. Department of Energy's Morgantown Energy Technology Center initiated a research and development testing and demonstration program to introduce the CO_2/sand frac process to gas well operators in the U.S. The stimulation testing was initiated with a 24-well stimulations planned in the eastern U.S. This paper focuses on the results of four 2-stage stimulations. Future plans include the testing and introduction of the CO_2/sand frac process to the western U.S. gas well operators beginning this fall with an 18-well test program in the Rockies. Early results of the first five CO_2/sand stimulations ever performed in the eastern U.S. show up to an 4.8 fold increase in production in the Pike County, Kentucky, study area[10]. Gas well operators in eastern Kentucky recognized the production benefits of the CO_2 process[11] and are considering stimulation of additional wells. Recent technological advances in the job execution procedures and design and operation of the closed system blender have recently been documented[12]. Industry advances in density measurements and blender equipment modification for higher sand concentrations have improved delivery of CO_2 and improved overall efficiency. Recent data from Canadian Fracmaster indicate that approximately 1,000 stimulations have been performed on oil and gas wells in Canada since 1982.

References and illustrations at end of paper

INTRODUCTION

The U.S. Department of Energy's Morgantown Energy Technology Center is responsible for implementation of a national natural gas research and development program. The key focus of the program is on product development through the introduction, development, and demonstration of new technology. The carbon dioxide/sand stimulation process is a good example. These new products must not only be demonstrated but a commercial service must be made available. This project involved the introduction of the CO_2/sand stimulation process to gas well operators in a fifteen well study area of candidate and control wells in Pike and Martin County, Kentucky (Figure 1). Two gas well operators offered four candidate wells drilled, cased, perforated, and ready for two-stage CO_2/sand stimulations. In addition, they had previously stimulated eleven control wells consisting of seven two-stage stimulations using nitrogen gas and four two-stage stimulations using nitrogen foam. The 15-well study

area was further delineated into 7 and 8-well groups which contained CO_2/sand, nitrogen gas, and nitrogen foam stimulated wells (Table 1). Analysis of production performance was made for Group 1, 2, and a composite of the entire study area.

DISCUSSION

Stimulation Treatments

There were three types of stimulation treatments involved in the study. Four wells were stimulated with CO_2/sand, seven with nitrogen, and four with nitrogen foam. The distribution within the two groups is indicated in Table 2.

CO_2/Sand

All 15 wells were stimulated with two stages across the entire Devonian Shale interval to provide a common basis for comparison. The selected CO_2/sand candidate well locations were close to wells with other types of stimulation to provide a comparison of production responses between CO_2/sand treatments with those from other stimulation types. The CO_2/sand stimulations in all four involved 120 tons of CO_2 per stage and up to 47,500 pounds of sand.

One of the four wells, FH179, differed significantly from the other fourteen wells in the study area group because of the apparent high stress state which resulted in high breakdown and treating pressures, limited ability to increase sand concentration, and later associated liquid production. The first stage treatment was aborted, and the interval was re-perforated with fresh acid which was subsequently swabbed and replaced with another volume of fresh acid prior to re-initiating the first stage treatment. The second attempt at treating the first stage also experienced high treating pressures, which limited the rate and sand volume. These behaviors were non-typical and considered to be the result of an anomalous geologic environment. The second stage responded similarly and a reduced sand volume was placed.

Sand volumes ranged from 35,000-47,500 pounds for the other six treatment stages (three wells) - averaging 43,300 pounds per stage. Maximum pump rates ranged from 44.6 to 53.5 barrels per minute, averaging 50.7. The pad volumes were all 100 barrels (19.2T), and the average sand concentrations ranged from 2.0 to 2.9 pounds per gallon. The maximum sand concentrations ranged from 4.0 to 5.2 pounds per gallon, averaging 4.7. The treatment specifics are presented in Tables 3, 4, and 5.

The maximum sand concentration was limited by the blender's mechanical capability. Because of the unique low stress environment of the Devonian Shale in the test area, the maximum sand concentration could have been greater. The equipment-limited-maximum sand concentrations of 5.2 pounds per gallon were realized at pump rates of 55 barrels per minute.

A pressure injection history with the associated sand concentration that is typical for the treatments for the last few stages is shown in Figure 2. It is representative for the state-of-the-art practices for the CO_2/sand process for the Devonian Shale within the test area.

Nitrogen Gas

The nitrogen treatments were all executed at 100 Mscf per minute with a total of 1.0 MMcf per stage. There was no proppant conveyed.

Nitrogen Foam

The nitrogen foam treatments ranged from 75 to 90 quality and from 50,000 to 120,000 pounds of sand were placed.

PRODUCTION COMPARISON

The four two-stage CO_2/sand stimulated wells have been on production for 9 months. Cumulative production from Groups 1 and 2 wells as identified in Figure 1 are compared on an individual group basis as well as a composite basis.

For Group 1 wells, individual cumulative well production by stimulation type are presented in Figures 3, 4, and 5. A composite of Group 1 wells is provided in Figure 6. Comparison of the data for CO_2/sand, nitrogen gas, and nitrogen foam fracs shows an average cumulative production after 9 months for CO_2/sand at 41.5 MMcf, nitrogen gas at 19.2 MMcf, and nitrogen foam at 6.1 MMcf. More than two-fold improvement for the CO_2/sand resulted when compared to nitrogen gas and a nearly seven-fold increase resulted when compared to nitrogen foam.

For Group 2, individual cumulative production plots by stimulation type are presented in Figures 7, 8, and 9. A composite of Group 2 wells is provided in Figure 10. Comparison of CO_2/sand, nitrogen gas, and nitrogen foam cumulative production shows an average cumulative production after 9 months for CO_2/sand at 14.3 MMcf, nitrogen gas at 10.8 MMcf, and nitrogen foam at 5.4 MMcf. The average cumulative production for the CO_2/sand fraced wells is strongly affected by wellbore fluids restricting production in well No. FH179. The operator plans a workover soon. However, the combined average cumulative production for CO_2/sand wells remains 32 percent higher than the nitrogen fraced wells and nearly two and a half times better than the nitrogen foam fraced wells. Production statistics are summarized in Table 6 for Groups 1 and 2. The descending order relative ranking of CO_2/sand, nitrogen gas, and nitrogen foam treatments was consistent for Group 1, Group 2, and the composite.

Further analysis of cumulative production in all 15 study area wells is presented in Figure 11. Average cumulative 9-months production for CO_2/sand, nitrogen gas, and nitrogen foam fracs were 27.9, 14.4, and 5.7 MMcf per well, respectively. Overall cumulative production improvement ratios for the 15 well study area was 1.9 for CO_2/sand versus nitrogen gas and 4.9 for CO_2/sand versus nitrogen foam. Incremental gas production was 13.5 and 22.2 MMcf, respectively. With this incremental production, the incremental cost of using CO_2/sand fracs is paid out in less than 9 months. Statistical data on cumulative production is presented in Table 7.

CONCLUSIONS

1. After 9 months of production, CO_2/sand fractured wells in the Pike County, Kentucky, study area produced 1.9 times more gas than nitrogen gas treated wells and produce 13.5 MMcf additional gas per well.

2. After 9 months of production, CO_2/sand fractured wells in the Pike County, Kentucky, study area produced 4.9 times more gas than nitrogen foam treated wells and produced 22.2 MMcf additional gas per well.

3. For the Pike County, Kentucky, study area, program payout times for the incremental cost of CO_2/sand stimulation is less than 9 months.

4. Both groups of wells in the Pike County, Kentucky, study area show consistent relative production improvements compared to the overall study area results.

ACKNOWLEDGEMENTS

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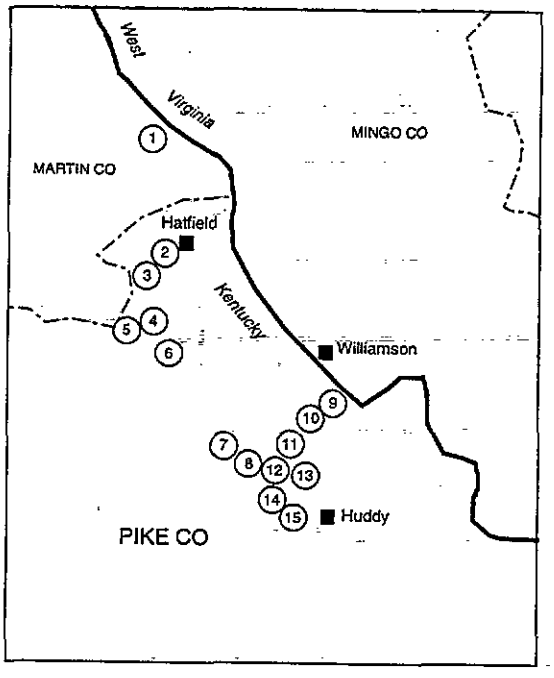

ID	Well	Completion
Group 1		
1	P1	CO_2/Sand - 455/475 SXS
2	S30	N_2 - w/o Sand
3	S29	N_2 - w/o Sand
4	S27	N_2 Foam - 500/500 SXS
5	S28	N_2 Foam - 740/700 SXS
6	S31	CO_2/Sand - 420/460 SXS
7	SB3	N_2 - w/o Sand
Group 2		
8	R5	N_2 - w/o Sand
9	V14	N_2 - w/o Sand
10	V15	N_2 - w/o Sand
11	FH180	N_2 - w/o Sand
12	FH179	CO_2/Sand - 56/298 SXS
13	FH177	CO_2/Sand - 435/350 SXS
14	T45	N_2 Foam - 1220/1220 SXS
15	T42	N_2 Foam - 1220/1285 SXS

Figure 1. Study Area, Pike Co., Kentucky

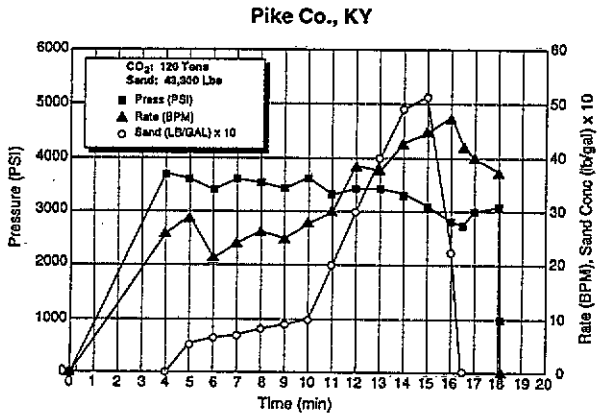

Figure 2. Pressure-Injection History - CO_2/Sand

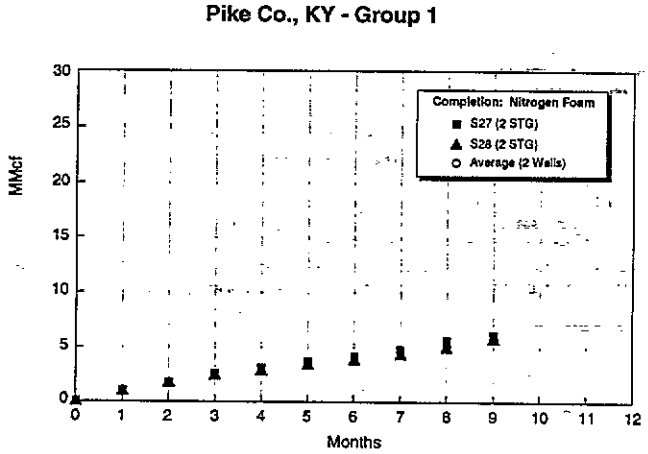

Figure 5. Cumulative Gas Production - Group 1 - Nitrogen Foam

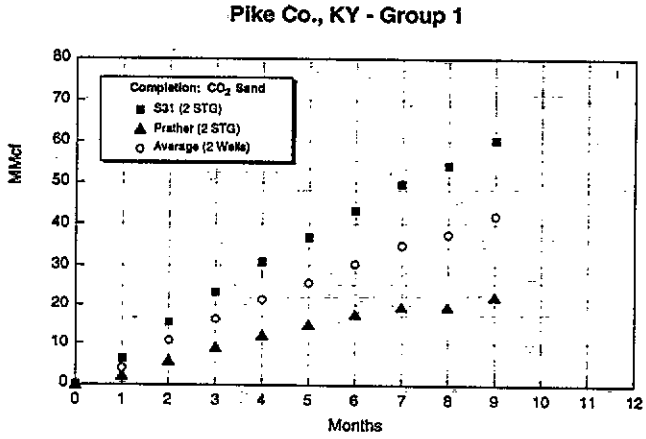

Figure 3. Cumulative Gas Production - Group 1 - CO_2/Sand

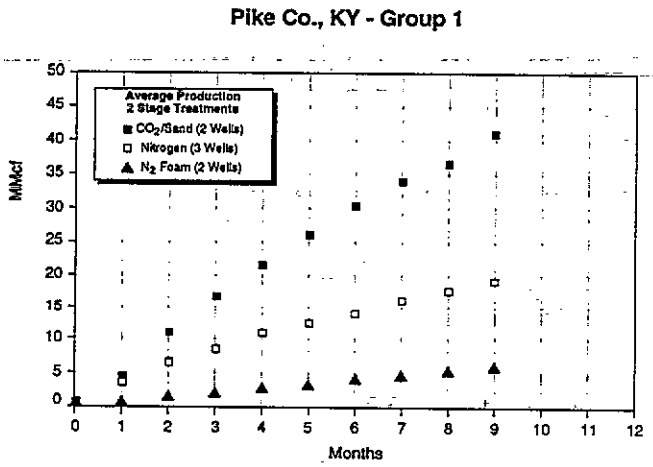

Figure 6. Cumulative Gas Production - Group 1 - Composite

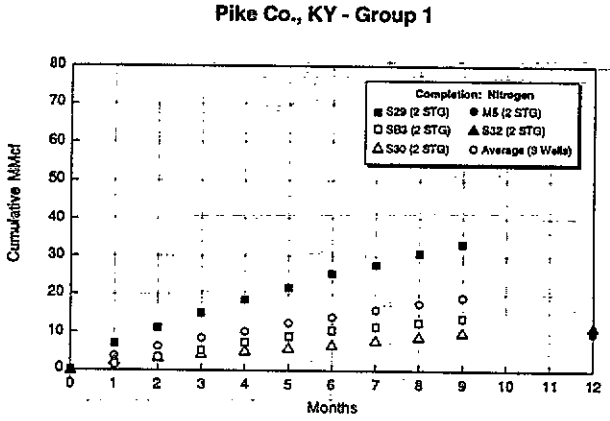

Figure 4. Cumulative Gas Production - Group 1 - Nitrogen Gas

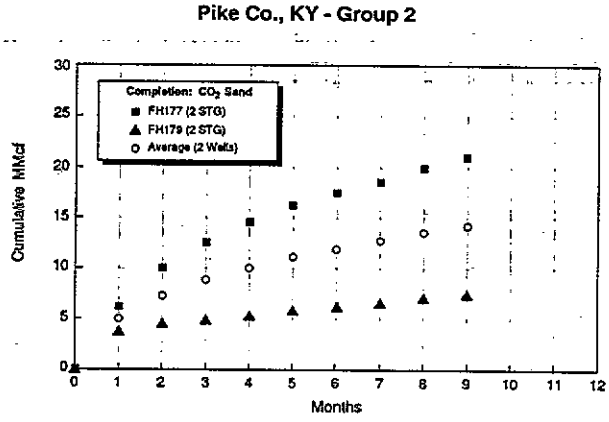

Figure 7. Cumulative Gas Production - Group 2 - CO_2/Sand

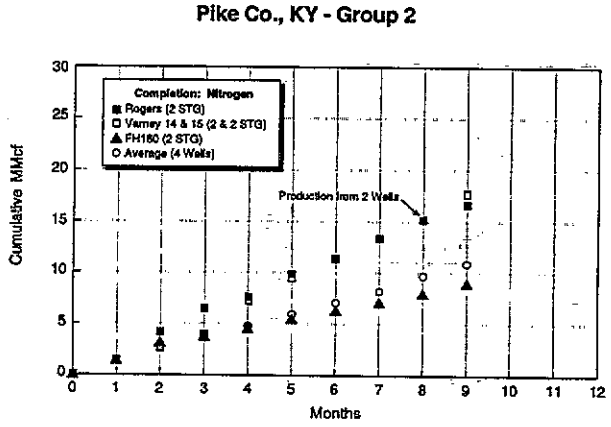

Figure 8. Cumulative Gas Production - Group 2 - Nitrogen Gas

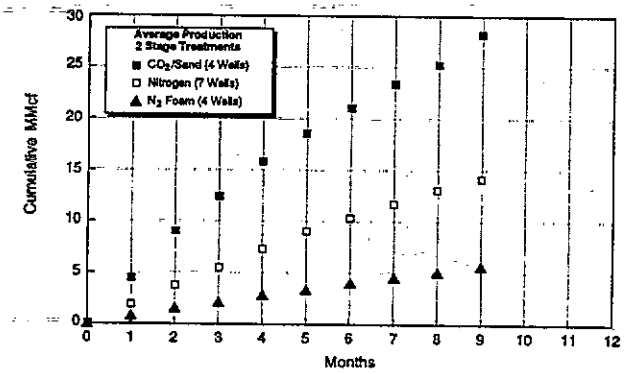

Figure 11. Cumulative Gas Production - Groups 1 & 2 - Composite

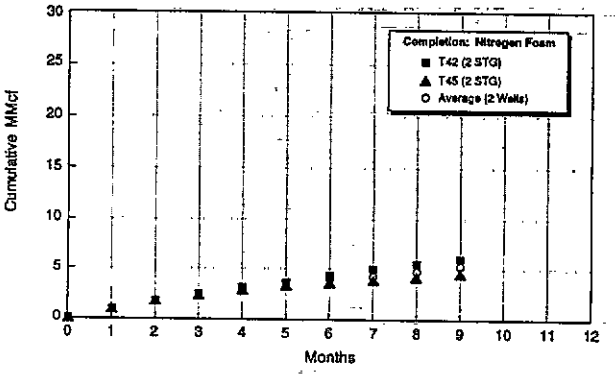

Figure 9. Cumulative Gas Production - Group 2 - Nitrogen Foam

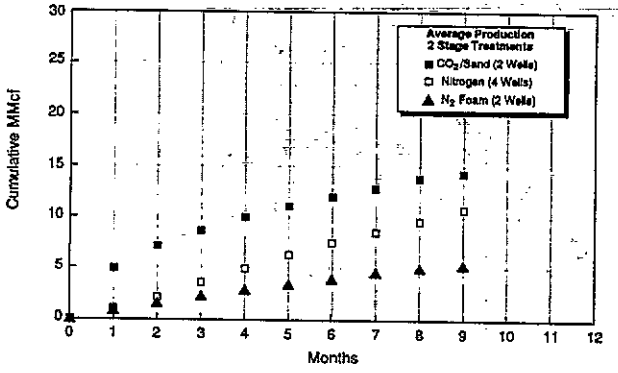

Figure 10. Cumulative Gas Production - Group 2 - Composite

TABLE 1
Study Area Well Identification

Stimulation Type	Group 1 Wells	Group 1 Number	Group 2 Wells	Group 2 Number
CO_2/Sand	S31, PI	2	FH177, FH179	2
N_2 Gas	S29, SB3, S30	3	R5, V14 & 15, FH180	4
N_2 Foam	S27, S28	2	T42 & 45	2
		7		8

TABLE 2
2-Stage Treatment Summary - Devonian Shale

Group	1	2	Total	Stage
CO_2/Sand	2	2	4	120 Tons CO_2 w/45,000 lbs Sand
N_2 Gas	3	4	7	1,000,000 cu ft w/0 lbs Sand
N_2 Foam	2	2	4	75 - 90q w/74 - 50,000 to 120,000 lbs Sand

15 Wells

TABLE 3
CO_2/Sand Treatment Summary

	Group 1		Group 2	
	S31	P1	FH177	FH179
CO_2 (Tons)	120/120	120/120	120/120	70/120
Sand (M Lb)	42/46	46/48	47/35	7/30
Rate (BPM)	44/35	48/38	45/29	25/30
SC (PPG)	2.9/2.6	2.7/2.8	2.6/2.0	1.4/1.7
9 Mo (MMcf)	60.3	22.7	21.0	7.5

TABLE 4
Stimulation Summary

	First Stage		Second Stage	
Well	S-31	Prather #1	S-31	Prather #1
CO/ST:	Pike/KY	Martin/KY	Pike/KY	Martin/KY
Permit #:	84819	84560	84819	84560
Elev Gl:	930	1005	930	1005
Tot Dpth:	3656	3673	3656	3673
Perfs:	20	20	20	21
Top:	3381	3332	2704	2679
Bot:	3552	3534	2805	2823
Interval:	171	202	101	144
Acid (Gal):	500	400	400	500
CO_2 (BBls):	571	571	571	571
(Tons):	120	120	120	120
Pad (BBLS):	100	100	102	100
SL (BBLS):	384	395	417	379
Flush (BBLS):	47	48	44	37
PMP (BBLS):	531	543	563	534
Sand (SXS):	420	455	460	475
Net (SXS):				
Mesh:	20/40	20/40	20/40	20/40
Rate (BPM) Avg:	43.8	47.7	35.1	37.9
Press (PSI) Avg:	2431	2788	3440	3029
Snd Conc (PPG) Avg:	2.9	2.7	2.6	2.8
Max:	4.2	5.0	5.2	5.2

TABLE 5
Stimulation Summary

	First Stage		Second Stage	
Well	FH 179	FH 177	FH 179	FH 177
CO/ST:	Pike/KY	Pike/KY	Pike/KY	Pike/KY
Permit #:	84574	84498	84574	84498
Tot Dpth:	3904	4041	3904	4041
Perfs:	30	19	19	19
Top:	3500	3616	2844	2885
Bot:	3870	3892	3183	3225
Interval:	370	276	339	340
Acid (Gal):	500	500	400	400
CO_2 (BBls):	308	571	571	571
(Tons):	69	120	120	120
Pad (BBLS):	133	102	100	104
SL (BBLS):	125	421	421	421
Flush (BBLS):	50	48	41	44
PMP (BBLS):	308	571	562	569
Sand (SXS):	73	465	300	350
Net (SXS):				
Mesh:	20/40	20/40	20/40	20/40
Rate (BPM) Avg:	25.0	44.8	30.0	29.0
Press (PSI) Avg:	3512	2920	3850	3894
Snd Conc (PPG) Avg:	1.4	2.6	1.7	2.0

TABLE 6
Cumulative Gas Production (MMcf)
(9 months)

Stimulation Type	Min	Max	Avg
Group 1			
CO_2/Sand	22.7	60.3	41.5
N_2 Gas	9.9	33.7	19.2
N_2 Foam	5.8	6.4	6.1
Group 2			
CO_2/Sand	7.5*	21.0	14.3
N_2 Gas	8.7	16.6	10.8
N_2 Foam	4.6	6.1	5.4

TABLE 7
Gas Production Comparisons - 9 Months

Pike Co., KY

Group	1	2	Combined Average (MMcf per Well)
CO_2/Sand	41.5	14.3	27.9
N_2 Gas	19.2	10.8	14.4
N_2 Foam	6.1	5.4	5.7

	Benefit Ratio	Incremental Gas (MMcf)
CO_2/Sand : N_2 Gas	1.9	13.5
CO_2/Sand : N_2 Foam	4.9	22.2